Quanser NI-ELVIS Trainer (QNET) Series:

QNET Experiment #07: HVAC ON-OFF Temperature Control

Heating, Ventilation, and Air Conditioning Trainer (HVACT)

Student Manual

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1. Laboratory Objectives

The objective of this experiment is to design an on-off temperature controller for the Heating, Ventilation, and Air Conditioning Trainer (HVACT) plant. The closed-loop system should regulate the desired chamber temperature.

2. References

[1] *NI-ELVIS User Manual*.
[2] *QNET-HVACT User Manual*.

3. Pre-Lab Assignments

This section must be performed, read, and understood before you go to the laboratory session.

3.1. ON-OFF Control Principle

Because of their simplicity of operation, on-off controllers are widely used in industry and found in many household applications, such as for example in thermostats and refrigerators. They do not require a specific knowledge or model of the system dynamics.

An on-off temperature controller is a single-loop controller which only has two states: ON and OFF. When in the on mode, its control action is at maximum power, and it can be seen as a high-gain controller.

3.2. ON-OFF Controller Design

The purpose of the laboratory is to design a controller that allows us to command and maintain the chamber temperature, T_c, "as closely as possible" to a desired level.

Table 1, below, provides a listing of the symbols and notations used in the on-off controller design, as presented in this laboratory.

Symbol	*Description*	*Unit*
T_c	Chamber Air Temperature	ºC
V_h	Heater Input Voltage	V
V_b	Blower Input Voltage	V
V_{h_max}	Maximum Heater Input Voltage	V
V_{b_max}	Maximum Blower Input Voltage	V

Table 1 On-Off Control Loop Nomenclature

The Heating, Ventilation, and Air Conditioning Trainer (HVACT) plant has one output to be controlled, the chamber temperature T_c. However although it actually has two inputs, that is to say the heater and blower voltages, not more than one should be active at a time, depending on whether the chamber needs to heated up or cooled down. This results in a "de-coupling" between the two inputs. Therefore, the HVAC plant is considered in this laboratory as a Single-Input-Single-Output (SISO) system.

Typically, the HVAC on-off control law used to heat up the chamber temperature, when required, is described below:

$$V_h(t) = V_{h\_max} \quad \text{and} \quad V_b(t) = 0 \qquad [1]$$

where t is the continuous time.

Similarly, the on-off control law used to cool down the chamber, through blowing of ambient air, is expressed as follows:

$$V_h(t) = 0 \quad \text{and} \quad V_b(t) = V_{b\_max} \qquad [2]$$

Also sometimes if the chamber air is "close enough" to the desired temperature setpoint, both actuators may be off, as formulated below:

$$V_h(t) = 0 \quad \text{and} \quad V_b(t) = 0 \qquad [3]$$

For both actuators, the maximum input voltages allowed, before reaching saturation, are given as follows:

$$V_{h\_max} = 4\ [V] \quad \text{and} \quad V_{b\_max} = 20\ [V] \qquad [4]$$

3.2.1. Control Switching Strategy

For a given temperature setpoint, T_{c_r}, the switching logic between the plant's two possible inputs, V_h and V_b, is determined by four trip temperatures, namely T_{h_on}, T_{h_off}, T_{b_on}, and T_{b_off}. This is illustrated in Figure 1, below. As it can be observed in Figure 1, a switching hysteresis has introduced for both actuators. In other words, both heater and blower can have different switch on and switch off temperatures.

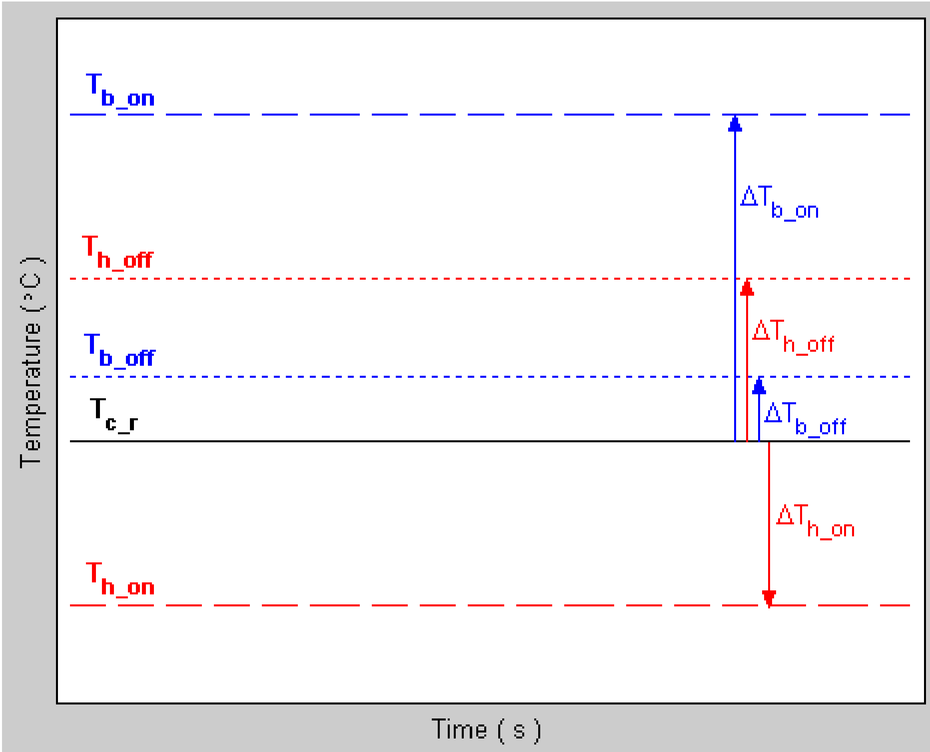


Figure 1 Blower And Heater On-Off Mode Regions

Table 2, below, provides a nomenclature of the parameters used for the on-off switching strategy, as presented in this laboratory, of the closed-loop Heating, Ventilation, and Air Conditioning (HVAC) plant.

Symbol	***Description***	***Unit***
T_{c_r}	Reference Chamber Temperature (i.e. Setpoint)	ºC
T_{h_on}	Heater Start Trip Temperature	ºC
T_{h_off}	Heater Stop Trip Temperature	ºC
T_{b_on}	Blower Start Trip Temperature	ºC
T_{b_off}	Blower Stop Trip Temperature	ºC
ΔT_{h_on}	Heater Start Trip Temperature Difference	ºC
ΔT_{h_off}	Heater Stop Trip Temperature Difference	ºC
ΔT_{b_on}	Blower Start Trip Temperature Difference	ºC
ΔT_{b_off}	Blower Stop Trip Temperature Difference	ºC

Symbol	*Description*	*Unit*
t	Continuous Time	s

Table 2 On-Off Switching Logic Parameter Nomenclature

To allow for a time-varying setpoint, $T_{c\_r}(t)$, the four trip temperatures are determined as function of temperature differences with regard to the given temperature reference.
The resulting on-off control parameters for both actuators are namely: ΔT_{h_on}, ΔT_{h_off}, ΔT_{b_on}, and ΔT_{b_off}. They are graphically represented in Figure 1, above, and mathematically defined by the four equations underneath.

The blower start trip temperature difference, ΔT_{b_on}, is the difference between the trip temperature T_{b_on} and the reference temperature T_{c_r}. This can be formulated as follows:

$$T_{b\_on}(t) = T_{c\_r}(t) + \Delta T_{b\_on} \qquad [5]$$

where t is the continuous time.

Likewise the blower stop trip temperature, T_{b_off}, can be expressed such as:

$$T_{b\_off}(t) = T_{c\_r}(t) + \Delta T_{b\_off} \qquad [6]$$

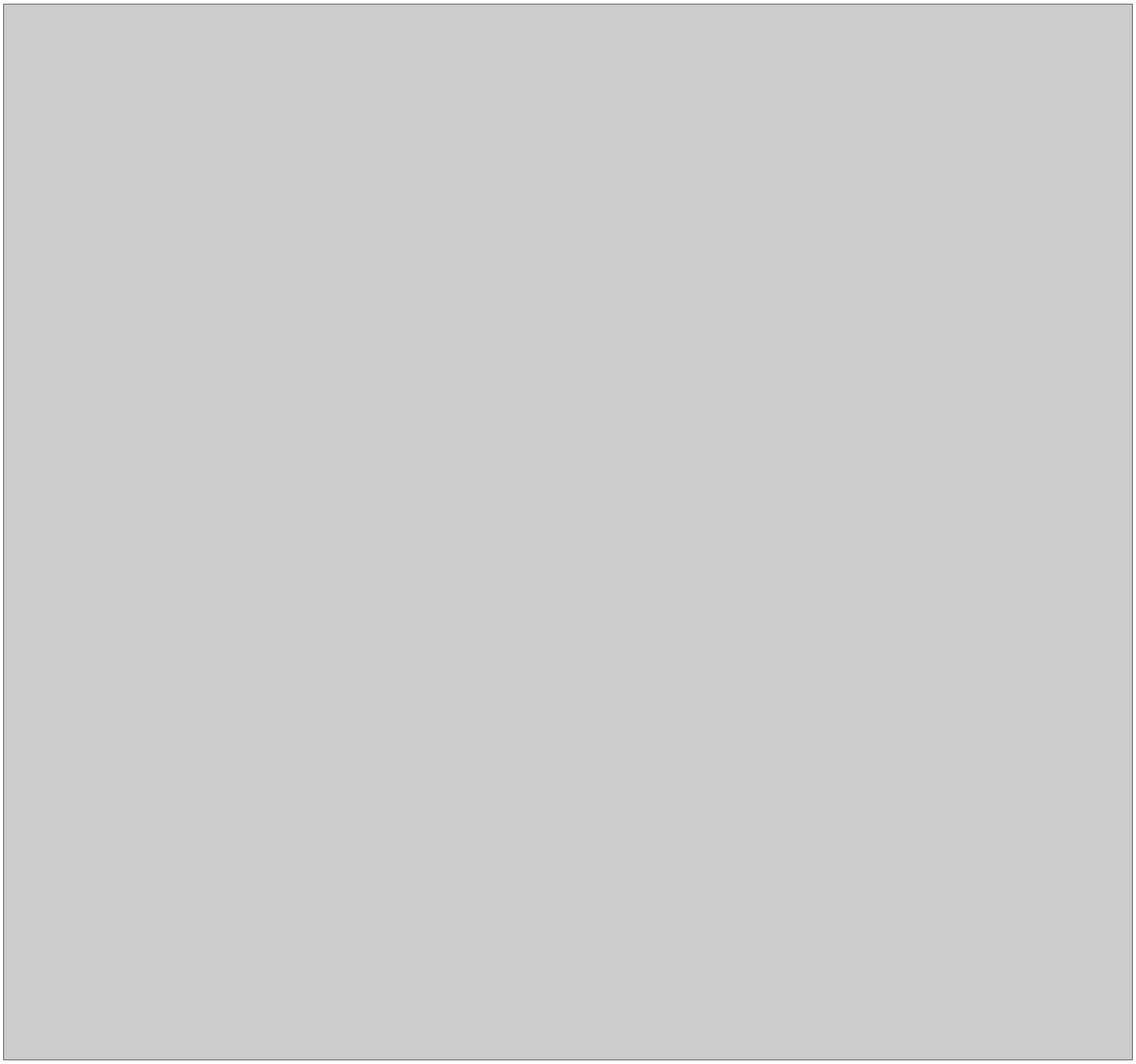
The heater start trip temperature T_{h_on} is defined as a function of the reference temperature T_{c_r} as follows:

$$T_{h\_on}(t) = T_{c\_r}(t) + \Delta T_{h\_on} \qquad [7]$$

Likewise, the heater stop trip temperature difference, ΔT_{h_off}, is the difference between the trip temperature T_{h_off} and the reference temperature T_{c_r}. This is shown below:

$$T_{h\_off}(t) = T_{c\_r}(t) + \Delta T_{h\_off} \qquad [8]$$

What conditions bearing on the four on-off control parameters must be respected so that the requirement of not having the two HVAC actuators on simultaneously is respected?



3.2.2. Heater Control Loop

During the heating process, the blower input voltage remains constant and equal to zero, as expressed below:

$$V_b(t) = 0 \tag{9}$$

where t is the continuous time.

The on-off control law with a switching hysteresis, as implemented for the chamber heating device (i.e. halogen lamp), is depicted in Figure 2, below.

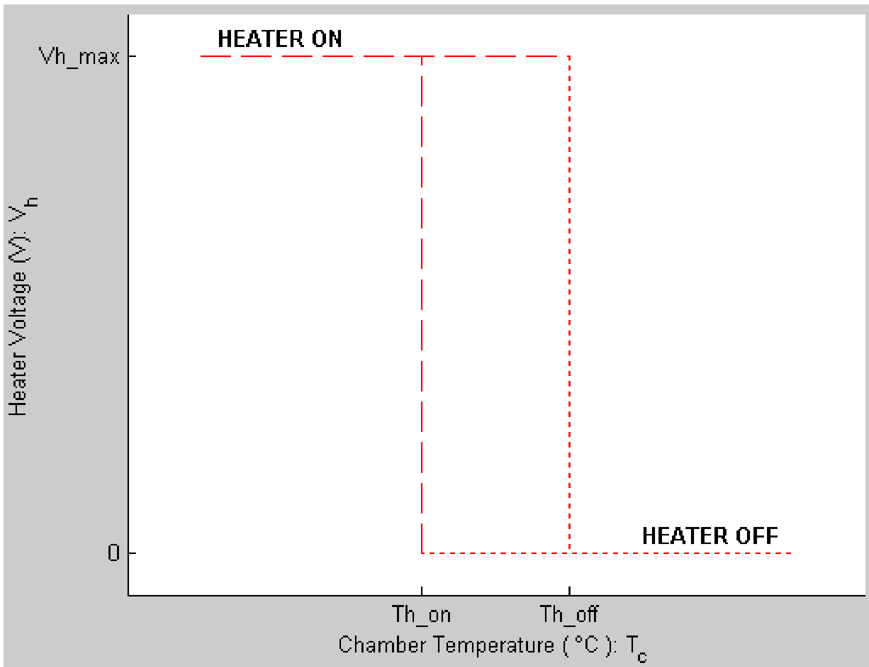


Figure 2 Heater Voltage Hysteresis

It can be observed in Figure 2, above, that when the heater voltage state, V_{h_state}, is ON, the heating actuator outputs maximum power with full control effort. The on-off control law commanding the heater input voltage, V_h, can be formulated as follows:

$$V_h(t) = \begin{cases} V_{h\_max} & V_{h\_state}(t) = ON \\ 0 & V_{h\_state}(t) = OFF \end{cases} \qquad [10]$$

As previously mentioned, start of heating is triggered if and only if the chamber temperature is lesser than the heater switch on temperature, that is to say: $T_c < T_{h\_on}$. The complete heater switching hysteresis can be characterized by the Boolean variable V_{h_state} as defined below:

$$V_{h\_state}(t) = \begin{cases} ON & T_c(t) < T_{h\_on}(t) \\ PREVIOUS & T_{h\_on}(t) < T_c(t) \text{ and } T_c(t) < T_{h\_off}(t) \\ OFF & T_{h\_off}(t) < T_c(t) \end{cases} \qquad [11]$$

where *PREVIOUS* is the previous value (either *ON* or *OFF*) of V_{h_state}; by default

PREVIOUS is *OFF*.

By definition of a hysteresis, the following relationship must be satisfied by the heater control parameters:

$$T_{h\_on} \leq T_{h\_off} \qquad [12]$$

This relationship is graphically represented in Figures 1 and 2, above.

3.2.3. Blower Control Loop

During the blowing process, the heater input voltage remains constant and equal to zero, as expressed below:

$$V_h(t) = 0 \qquad [13]$$

The on-off control law with switching hysteresis, as implemented for the chamber blowing device (i.e. fan), is depicted in Figure 3, below.

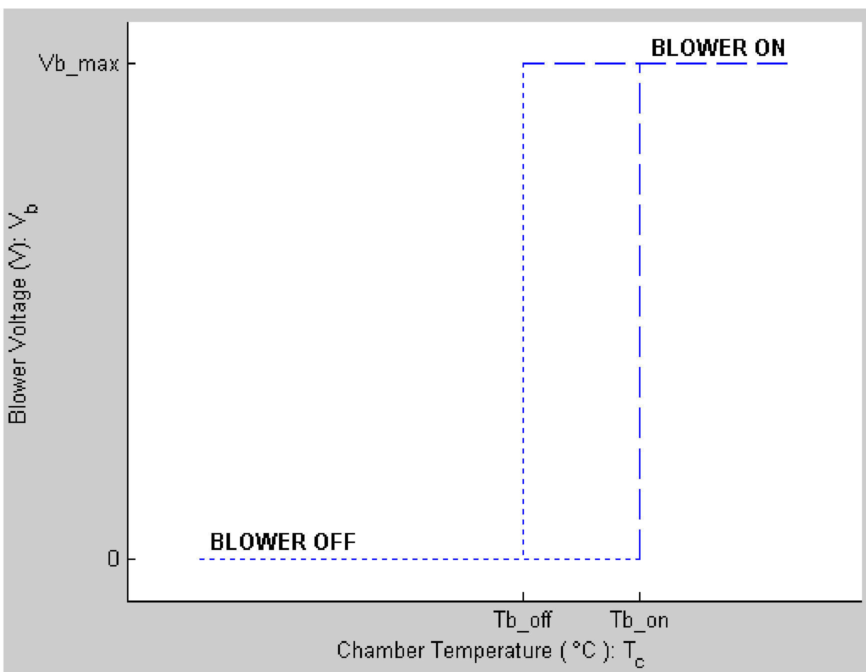


Figure 3 Blower Voltage Hysteresis

It can be observed in Figure 3, above, that when the blower voltage state, V_{b_state}, is ON, the blowing actuator outputs maximum power with full control effort. The on-off control law

commanding the blower input voltage, V_b, can be formulated as follows:

$$V_b(t) = \begin{cases} V_{b\_max} & V_{b\_state}(t) = ON \\ 0 & V_{b\_state}(t) = OFF \end{cases} \quad [14]$$

As previously mentioned, start of blowing is triggered if and only if the chamber temperature is greater than the blower switch on temperature, that is to say: $T_c \geq T_{b\_on}$. The complete blower switching hysteresis can be characterized by the Boolean variable V_{b_state} as defined below:

$$V_{b\_state}(t) = \begin{cases} ON & T_{b\_on}(t) < T_c(t) \\ PREVIOUS & T_{b\_off}(t) < T_c(t) \text{ and } T_c(t) < T_{b\_on}(t) \\ OFF & T_c(t) < T_{b\_off}(t) \end{cases} \quad [15]$$

where *PREVIOUS* is the previous value (either *ON* or *OFF*) of V_{b_state}; by default *PREVIOUS* is *OFF*.

By definition of the blower hysteresis, the switch on point value must be greater than or equal to the switch off point. This is formulated with the blower control parameters by the following relationship:

$$T_{b\_off} \leq T_{b\_on} \quad [16]$$

This relationship is graphically represented in Figures 1 and 3, above.

3.2.4. Controller Specifications

The designed control loop should operate around the following operating chamber temperature, T_{c_op}:

$$T_{c\_op} = 26.0 \ [degC] \quad [17]$$

The following controller design requirements are to be satisfied by the chamber temperature in response to a square wave temperature setpoint, T_{c_r}, with an amplitude, ΔT_{c_r}, of 2 °C centered around T_{c_op}.

1. The output temperature peak-to-peak oscillation, ΔT_{c_p2p}, around the desired setpoint level should be such as:

$$\Delta T_{c\_p2p} \leq 0.5 \ [degC] \quad [18]$$

2. The output temperature oscillation period, T_{Tc}, around the desired setpoint level should

satisfy the relationship below:

$$4\ [s] < T_{Tc} \quad [19]$$

4. In-Lab Session

4.1. System Hardware Configuration

This in-lab session is performed using the NI-ELVIS system equipped with a QNET-HVACT board and the Quanser Virtual Instrument (VI) controller file *QNET_HVAC_Lab_07_ON_OFF_Control.vi*. Please refer to Reference [2] for the setup and wiring information required to carry out the present control laboratory. Reference [2] also provides the specifications and a description of the main components composing your system.

Before beginning the lab session, ensure the system is configured as follows:

QNET HVACT module is connected to the ELVIS.
ELVIS Communication Switch is set to BYPASS.
DC power supply is connected to the QNET HVAC Trainer module.
The 4 LEDs +B, +15V, -15V, +5V on the QNET module should be ON.

4.2. Experimental Procedure

Please follow the steps described below:

Step 1. Read through Section 4.1 and go through the setup guide in Reference [2].
Step 2. Open the VI controller file *QNET_HVAC_Lab_07_ON_OFF_Control.vi*. You should obtain a front panel similar to the one shown in Figure 4, below. The default sampling rate for the implemented digital controller is 250 Hz. However, you can adjust it to your system's computing power. Please refer to Reference [1] for a complete system's description. The chamber temperature, directly sensed by the thermistor, is plotted on a chart (in blue) as well as displayed in a Numeric Indicator located in the *Chamber Temperature* front panel box. The values are in degrees Celsius (°C).

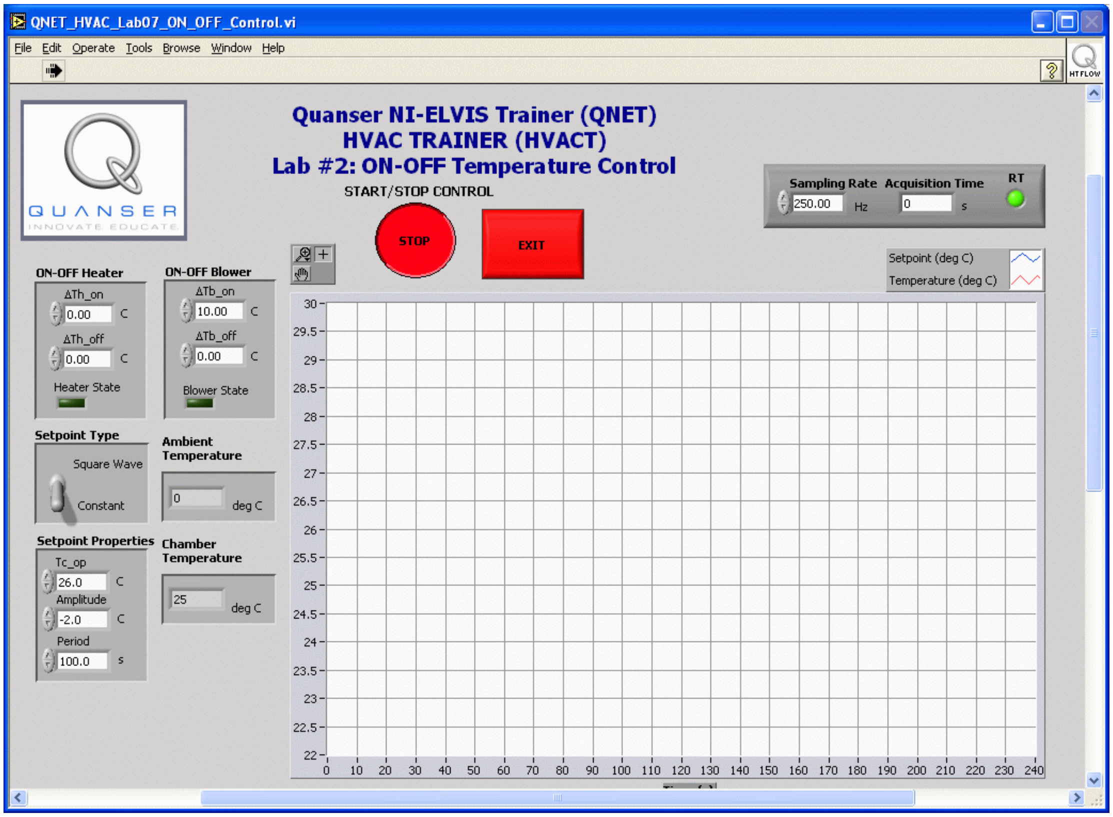


Figure 4 Front Panel Used for the QNET-HVACT ON-OFF Temperature Control Laboratory

Step 3. When you first open the *QNET_HVAC_Lab_07_ON_OFF_Control.vi* controller file, the controller gains are not yet tuned. Your default on-off controller parameters should be similar to the ones provided in Table 3, below.

ΔT_{h_on} [°C]	ΔT_{h_off} [°C]	ΔT_{b_on} [°C]	ΔT_{b_off} [°C]
0.00	0.00	10.00	0.00

Table 3 "Un-Tuned" On-Off Controller Parameters

This section experimentally investigates the regulation of a constant temperature inside the chamber. The vertical toggle switch in the *Setpoint Type* box allows you to choose between a *Square Wave* or a *Constant* type of reference temperature, T_{c_r}. In a first time, ensure that it is set to the *Constant* position. The temperature setpoint is also plotted on the front panel chart (in red). The desired regulation level should be set to the operating chamber temperature, T_{c_op}, as defined by Equation [17]. Use the Numeric Controls of the *Setpoint Properties* box to set the chamber operating temperature, T_{c_op}, to 26 °C (as expressed in Equation [17]), and the constant

Amplitude to 0 °C. Specifically the default setpoint properties parameters are expressed in Table 4, below.

Signal Type	T_{c_op} [°C]	Amplitude: ΔT_{c_r} [°C]	Period [s]
Constant	26.0	0.0	100.0

Table 4 Default Temperature Setpoint Parameters

Step 4. The purpose of this experiment is to use the heater alone to regulate the chamber temperature, T_c, at the desired T_{c_op}. Setting ΔT_{b_on} to 10 °C disables the fan by ensuring that it will not be switched on by the controller, since the resulting T_{b_on} is 36 °C. Chamber cooling is achieves when the heater is off by natural heat dissipation due to conduction and convection. In this experiment while regulating T_c, you will change the heater hysteresis parameters on-line and observe their effect on the actual temperature response. Table 5, below, displays the four sets, each corresponding to a different *Iteration #*, of hysteresis parameters to try and compare. You will first start, in *Iteration #* 1, with no hysteresis (i.e. $T_{h\_on} = T_{h\_off}$). In the *ON-OFF Heater* box, ensure that use the two Numeric Controls labeled *ΔTh_on* and *ΔTh_off* corresponding to both hysteresis parameters ΔT_{h_on} and ΔT_{h_off} are properly set (here to zero).

Iteration #	ΔT_{h_on} [°C]	ΔT_{h_off} [°C]	Time [s]
1	0.0	0.0	
2	-0.2	0.0	
3	-0.4	0.0	
4	-0.4	0.25	

Table 5 Heater Hysteresis Iteration Parameters

Step 5. Run the LabVIEW VI (Ctrl+R) to start the controller. The initially green START push button should now show as a red STOP button that you can trigger to pause the controller execution. With the control action active, the chamber temperature should now go up and down to roughly regulate the desired constant setpoint. For each set of hysteresis parameters given in Table 5, observe and characterize the resulting actual temperature response, as plotted on the front panel chart. You should also observe when the Heater is turned on or off, as materialized by the *Heater* LED on the front panel. Get a feel of the corresponding switching frequency of the heater control voltage. Once you have acquired enough data to characterize the control output dynamics you can move on to the next *Iteration #*. Once *Iteration #* 4 is complete, make a screen capture of the obtained response plot to measure the acquired data and join a printout to your report. DO NOT press *EXIT* and do not stop the VI! Fill up in

Table 5 the time range of your actual response plot corresponding to each *Iteration #*.

Step 6. Compare and explain the actual temperature response obtained for each one of the four previous sets of hysteresis parameters. Your discussion should take into account the amplitude and frequency of any output oscillation as well as the switching frequency of the heater control signal (indicated by the blinking of the *Heater* LED).

Step 7. Do you see any practical reason why the heater hysteresis width should have a specified minimum level?

Hint:

The hysteresis width can be defined as follows:

$$\left|\,|\Delta T_{h\_on}| - |\Delta T_{h\_off}|\,\right|$$

where | | is the absolute value function.

Step 8. Do you see a controller design trade-off in tuning/choosing the actuator hysteresis limits?

Hint:

Consider the response performance with regard to the control effort spent.

Step 9. You can stop the VI by pressing the red *EXIT* button on the front panel.

Step 10. Your previous observations and conclusions regarding the working principles and tuning of the heater hysteresis, apply similarly to the blower switching hysteresis.

Step 11. The goal of this experiment is to tune the on-off controller for both actuators so that the output temperature tracks a desired square wave setpoint with the level of performance previously specified in the design requirements. For the VI to generate the proper setpoint, ensure that the vertical toggle switch in the *Setpoint Type* box is set to the *Square Wave* position. Use the Numeric Controls of the *Setpoint Properties* box to set the chamber operating temperature, T_{c_op}, to 26 °C (as expressed in Equation [17]), the square wave *Amplitude* to -2 °C, and *Period* to 100 seconds. Specifically the setpoint properties parameters are expressed in Table 6, below.

Signal Type	T_{c_op} [°C]	Amplitude [°C]	Period [s]
Square Wave	26.0	-2.0	100.0

Table 6 Temperature Setpoint Parameters

Step 12. Start the controller by running the LabVIEW VI (Ctrl+R) and tune experimentally, on-the-fly, the hysteresis limits on both actuators so that the chamber temperature tracks the temperature setpoint while respecting the design specifications. The software applies square wave temperature setpoints to the closed-loop control system and plots both setpoint and actual chamber temperature over a 240-second time range. Observe the way the system switches between the two actuators (i.e. lamp and fan) in order for the chamber temperature to track the desired square wave setpoint around the operating level T_{c_op}.

Step 13. Summarize your final tuned controller parameters by filling up Table 7 as shown below.

ΔT_{h_on} [°C]	ΔT_{h_off} [°C]	ΔT_{b_on} [°C]	ΔT_{b_off} [°C]

Table 7 Tuned Controller Parameters

Step 14. Let the system run until you have plotted on the chart the temperature response to at least three periods of the setpoint. DO NOT press *EXIT* and do not stop the VI!

Step 15. Make a screen capture of the obtained step response plot and join a printout to your report. This capture can be used to make measurements.

Step 16. Does the closed-loop system track the desired square wave setpoint accurately? Comment on the symmetry (or lack) of the temperature response between heating and blowing steps. Explain.

Step 17. You should now measure and determine your system performance from the capture of the response plot taken.

Step 18. Do the limit cycle peak-to-peak amplitude and frequency measured for both levels of regulation meet the required specifications? Explain your observations.

Step 19. If the design requirements defined by Equations [18] and [19] are still not satisfied, you should re-iterate your manual trial-and-error procedure to fine tune the controller parameters of Table 7 until the response performance improves to the desired requirements. Include in your laboratory report your final tuning parameters, experimental plots and results, as well as the measured system performance criteria satisfying the specifications.

Step 20. Once all your experimental results are obtained, shut off the PROTOTYPING POWER BOARD switch and the SYSTEM POWER switch at the back of the ELVIS unit. Unplug the module AC cord. Then, stop the VI by pressing the red EXIT button. Ensure that you have all the data required for your laboratory report before leaving the laboratory session.